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DEVELOPMENT OF A LIMITED AREA FINE-MESH PREDICTION MODEL

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ABSTRACT

A limited area, fine-mesh, primitive equation barotropic model has been integrated using data observed at 500 mb. The lateral boundary conditions used in the model required that no change occur on the boundary during the 24-hr forecast. The predictions compare favorably with those obtained with the barotropic and baroclinic models in operational use at the National Meteorological Center.

1. INTRODUCTION

Two clearly desirable objectives can be set for applied research in numerical weather prediction. First, the frequent underestimation of the displacement of relatively high wave-number disturbances should be corrected. Secondly, the variability in observational data density should be taken into account in order to optimize the utilization of initial data in short-range predictions. This paper reports the success of an effort directed toward achieving these objectives.

The role of simple truncation error in the underestimation of the phase speed of disturbances is readily demonstrated. In order to overcome this problem in the operational, filtered barotropic model, Shuman and Vanderman (1965) developed a higher order approximation to the Jacobian. In the case of the primitive equation models, the problem of achieving computational stability was of higher priority. At present, higher order difference approximations could be developed for the National Meteorological Center (NMC) primitive equation (PE) model (Shuman and Hovermale, 1968), but the constraints imposed by the computational code used in the model seem to favor the alternative course of reducing the spatial separation of the grid points.

The use of a finer mesh also appears to provide a feasible approach to the satisfaction of the second objective. The greater resolution available with a fine-mesh grid suggests that one might achieve a more faithful delineation of the initial state of the atmosphere as observed within the data-dense portions of the region of integration. This is a somewhat superficial view, but it has validity as a first-order approximation.

2. BACKGROUND AND RELATED RESEARCH

If one seeks to match grid resolution to data density, the use of a variable mesh size seems appropriate. Thus, one might use a coarse mesh over most of the oceans and a fine mesh over the populated continental areas. The limited area, or "window-grid" method (Howcroft, 1966), could be used to confine the fine mesh to the data-dense region; a hemispheric, coarse-mesh model would be employed to provide suitable boundary conditions. (The grid-telescoping scheme discussed by Hill, 1968, is a logical extension of this idea.)

In a recent study by Bushby and Timpson (1967), the limited area approach was adapted to a primitive equation baroclinic model. By making the integration region sufficiently large, Bushby and Timpson sought to circumvent the requirement for specifying accurate boundary conditions. Shuman (1962) had previously shown that a primitive equation model could be integrated over a limited area by using boundary conditions that are only appropriate for the "gravitational mode." Both of these studies indicated that a significant amount of noise occcurred in the numerical solutions. Bushby and Timpson controlled the greater part of the noise through their use of the staggered-grid method, which possesses smoothing characteristics, and by a filtering scheme for controlling the solution near the boundary. Shuman used the filtered-factor difference method and found that in spite of the presence of a great deal of noise in the unprocessed fields the meteorologically significant flow was easily recovered from the predicted wind field.

Most recently, Wang et al. (1968) have initiated a study directed toward the solution of the problem of blending a limited-area, fine-mesh primitive equation model with boundary conditions obtained from a hemispheric prediction made with a coarse-mesh model. Their objective is the development of a high resolution model covering a very limited horizontal area, a situation in which one cannot ignore the influences of changes in the synoptic mode on the boundaries of the limited area.

It is our belief that an operational requirement does exist for a model with only a modest increase in grid resolution, one which can be used to attain just those objectives outlined in the introductory paragraph. To attain these objectives within NMC's present operational environment, it would be desirable for the limited-area model to function independently of a hemispheric coarse-mesh model. Our effort may therefore be distinguished from that being pursued by Wang et al. Bushby and Timpson seem to be devoting their effort toward more basic research objectives, such as the study of subsynoptic scale precipitation. Since we shall be using a primitive equation model, the previously cited results of Howcroft and Hill with filtered models are not directly applicable to our work.

3. THE MODEL

It is well known that the configuration of the geopotential contours on the 500-mb surface in extratropical regions may be predicted with considerable skill through the application of the "barotropic model." The similarity between the dynamics of an equivalent barotropic atmosphere and of a homogeneous, incompressible fluid with a free surface is also well known. On these bases, it has been assumed that one may reasonably seek to apply the following differential equations to data observed at 500 mb:

$$\partial h/\partial t = -\operatorname{div}(\mathbf{v}h) \tag{1}$$

and

$$\partial \mathbf{v}/\partial t = -\mathbf{v} \cdot \nabla \mathbf{v} - f\mathbf{k}\times\mathbf{v} - g\nabla h, \tag{2}$$

where h is the geopotential height of the 500-mb surface, $\mathbf{v}$ is the horizontal velocity vector at 500 mb, f is the Coriolis parameter, g is the gravity acceleration constant, and $\mathbf{k}$ is the unit vertical vector.

This system of equations is expressed in polar-stereographic map coordinates. The transformation into a set of finite-difference equations is accomplished by using the "semi-momentum" scheme (Shuman and Hovermale, 1968) for the spatial derivatives and the Euler-backward scheme (Kurihara, 1965) for the time derivatives.

The spatial finite-difference grid, on which the equations are solved, is contained within the rectangle shown in figure 1. The distance between neighboring grid points (note the grid scale in the lower right of the rectangle) is 190.5 km at 60° N. latitude. This is one-half of the spacing used in the hemispheric models at NMC. The particular orientation of the grid was dictated by the necessity of using the operational analysis data which are available only within the octagon shown in figure 1 and by a desire to include most of the conterminous United States.

The equations are solved at all of the grid points that are located at least one grid interval inside the boundary. On the boundary, the variables are kept unchanged from their initial values. All of the forecast fields are subject to a smoother prior to output; this results in the loss of the data on three points all around the rectangular boundary. The unsmoothed forecasts contain a large amount of high wave-number noise, but only one pass of a 49-point linear operator[1] is adequate to produce apparently noise-free fields.

In setting up this model, our principal concern was with the formulation of suitable boundary conditions. As far as slow-moving meteorological systems were concerned, it was anticipated that the errors in a 24-hr forecast would be confined to the region in close proximity to the boundaries. On the other hand, the rapidly moving gravity oscillations were of major concern. If due to the prescribed boundary conditions, these waves were to be aliased into long waves with considerable amplitude, the usefulness of the forecasts would be nullified.

A series of one-dimensional numerical experiments with the linear wave equation was conducted to examine how short waves would propagate under alternatively specified boundary conditions. Our analyses were largely on a "cut and try" basis, but by a heuristic argument the conclusion was reached that temporally constant boundary values would be suitable. The two-dimensional results with the PE barotropic model discussed in the next section validated that conclusion.

[1] See Appendix.

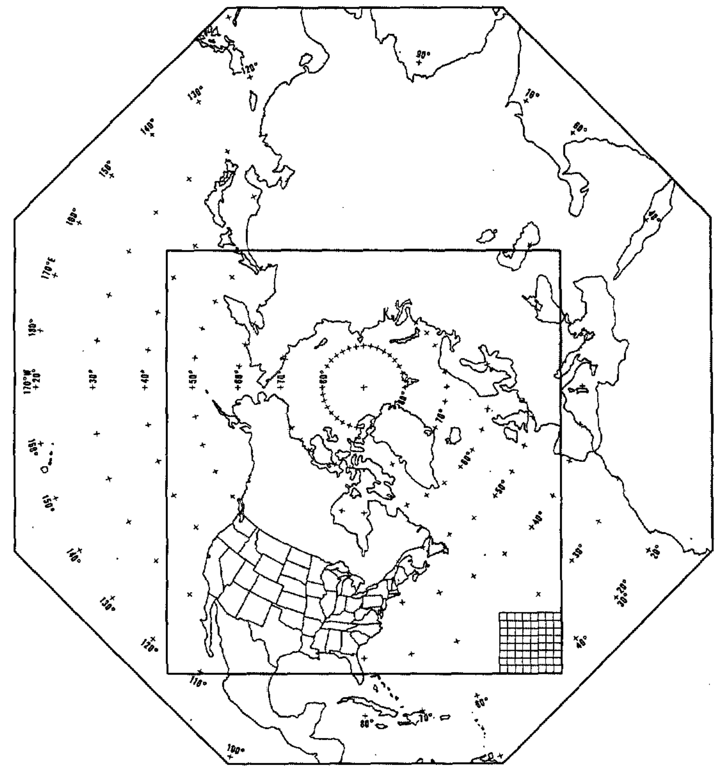

FIGURE 1.—Polar stereographic map of the Northern Hemisphere showing the octagon within which data were available. Also shown is the rectangular boundary of the limited-area fine mesh within which the model equations were solved. In the lower right-hand part of the rectangle a portion of the fine-mesh grid is illustrated.

Finally, a word concerning the absence from the model of an "initialization" procedure is called for. The motivation for employing "balanced" winds as the initial data in the integration of primitive equation models is largely negative in content. It is based on the expectation (actually observed in some numerical experiments) that the use of unbalanced winds will lead to the rapid and excessive growth of gravity-inertial oscillations. Experience (Dey, 1969) with the Euler-backward method for integrating a PE barotropic model on a global grid with unbalanced winds gave us a strong basis for discounting this problem. The filtering property of the Euler-backward method appears to be sufficiently selective so as to control the high-frequency gravity mode, but not to modify seriously the low-frequency meteorological modes during a 24-hr forecast.

4. FORECAST RESULTS

The model has been run on a number of cases with remarkably good results; however, for simplicity, only one typical case will be presented here. This case was chosen for the initial experiment because the contour field displayed a small-scale rapidly moving feature over central North America.

The initial data were extracted from the operational analyses of 500-mb wind and height. These fields were interpolated onto the fine-mesh grid points using a biquadratic formula. It should be noted that the winds were *not* obtained from the balance equation. In regions where

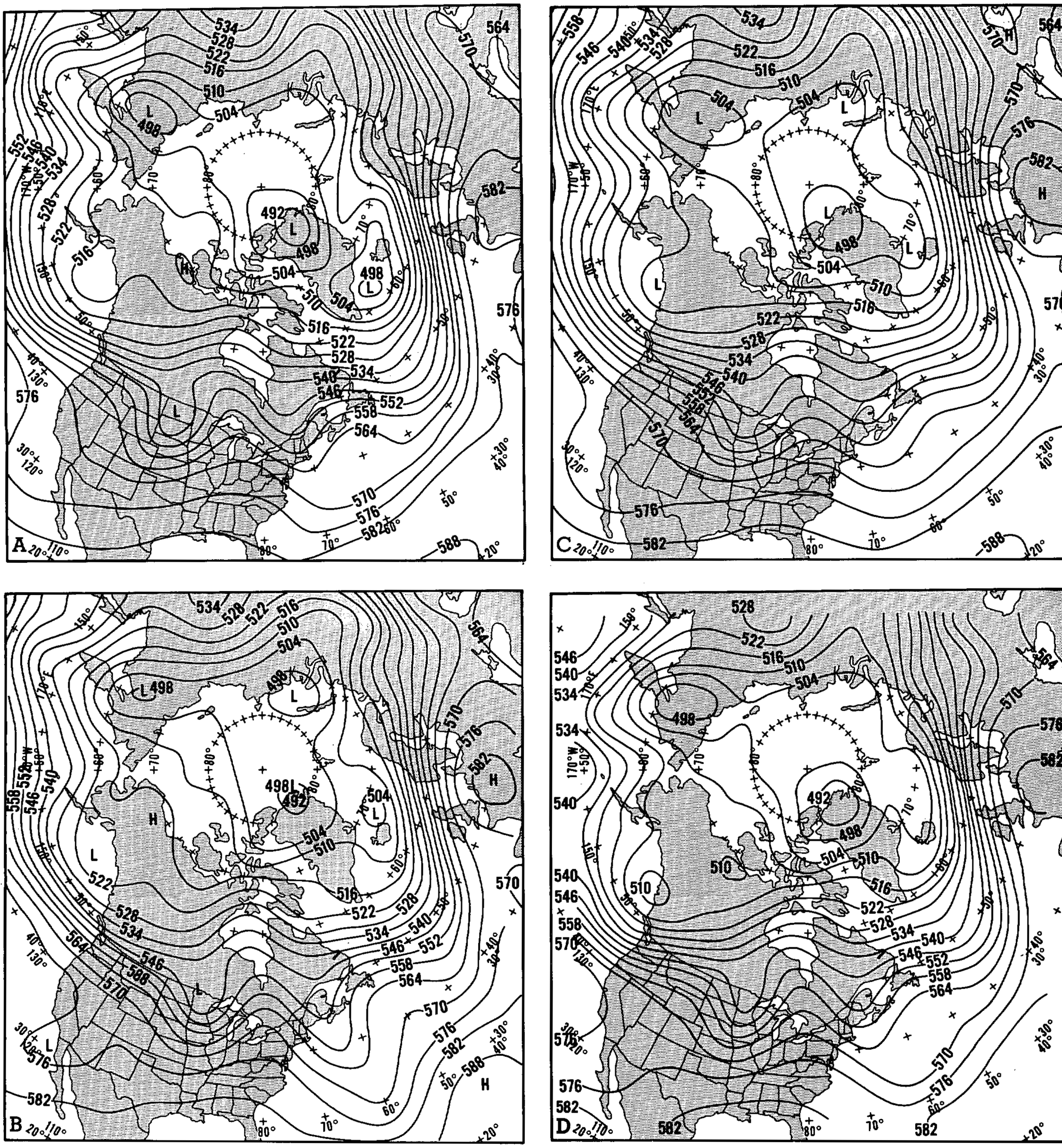

FIGURE 2.—(A) the initial configuration of the 500-mb geopotential height field is shown after it was interpolated onto the fine mesh. The contours are labeled in decameters. This analysis is for 1200 GMT, Mar. 27, 1968; (B) the 500-mb geopotential height field observed at 0000 GMT, Mar. 28, 1968; (C) the 500-mb geopotential height field as predicted to verify at 12 hr after the initial time by the operational National Meteorological Center filtered barotropic model; (D) the 500-mb geopotential height field as predicted to verify at 12 hr after the initial time by the fine-mesh primitive equation barotropic model.

observations are available, the analyzed winds reflect these observations. In regions of no data, the analyzed winds are nearly geostrophic.

Figure 2 contains four panels labeled A through D. In figure 2A, the field of 500-mb geopotential height is shown as it was analyzed at 1200 GMT, Mar. 27, 1968, the initial time of the forecast. In figure 2B, the analyzed field 12 hr later is shown.

The feature of primary interest is the short wave which moves from the Dakotas eastward to Minnesota during the 12-hr period at a speed of 30 kt. In figures 2C and 2D, the 12-hr forecasts made with the regular-mesh,

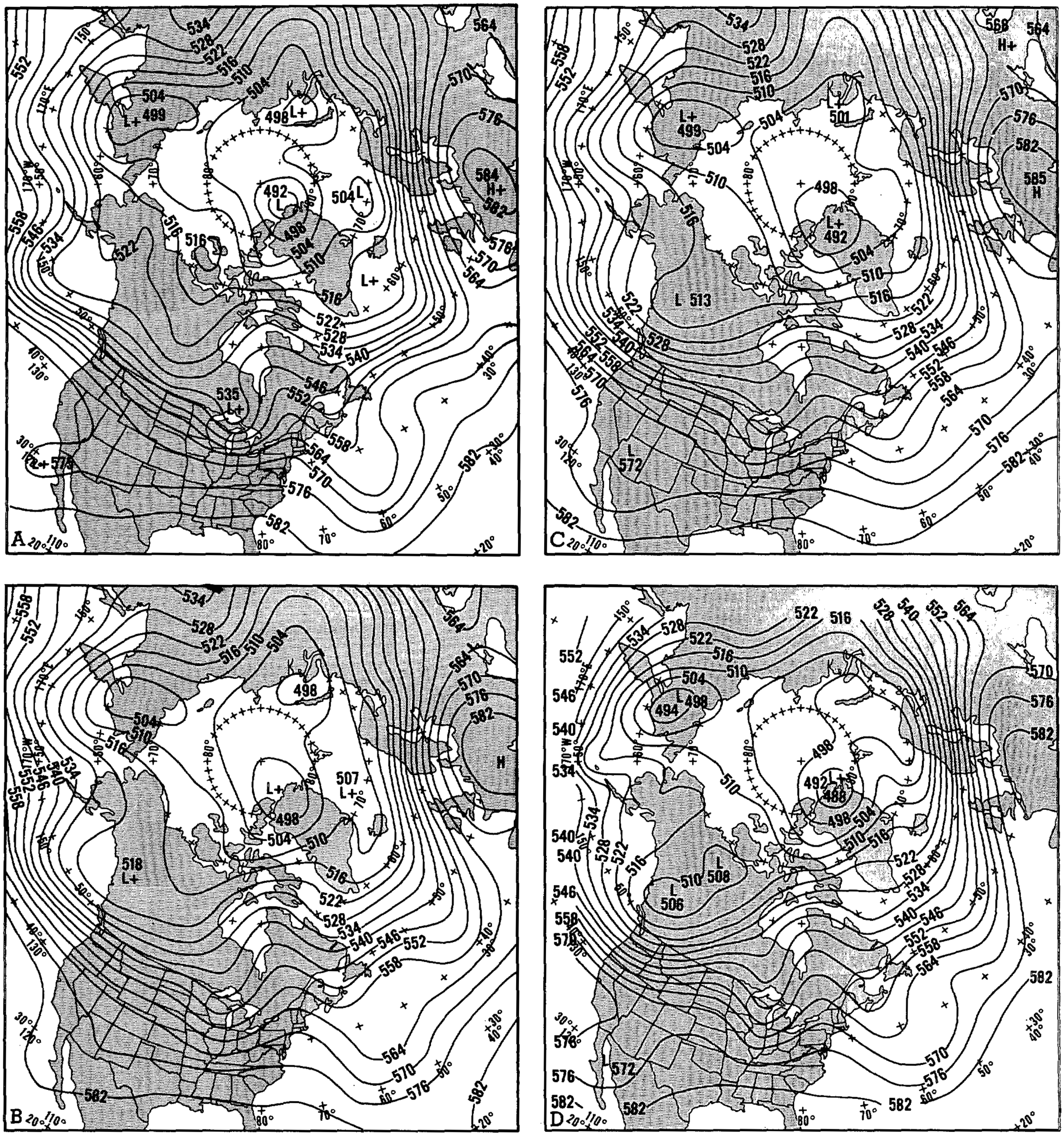

FIGURE 3.—(A) the 500-mb geopotential height field observed at 1200 GMT, Mar. 28, 1968; (B) the 500-mb geopotential height field as predicted by the operational National Meteorological Center primitive equation baroclinic model to verify at 24 hr after the initial time; (C) the 500-mb geopotential height field as predicted to verify 24 hr after the initial time by the operational National Meteorological Center filtered barotropic model; (D) the 500-mb geopotential height field as predicted to verify 24 hr after the initial time by the fine-mesh primitive equation barotropic model.

filtered barotropic and the fine-mesh PE barotropic models are shown. There is not much difference in the trough position predicted by the two barotropic models. One should again note that the filtered barotropic model employs a truncation error control in its Jacobian approximation.

There is a noteworthy distinction between the two forecasts in the sharpness of the trough over northern Minnesota. The fine-mesh model correctly retained the strong cyclonic curvature of the contours in the vicinity of the trough, whereas the filtered barotropic model reduced the curvature and filled the trough. This added detail suggests that the finer mesh serves to retain smaller scale features in the flow pattern as well as to provide higher accuracy in computed phase velocity.

Figures 3A through 3D display the 24-hr forecasts made with the fine-mesh PE barotropic, the regular-mesh PE baroclinic and the filtered barotropic models, as well as the verifying analysis.

The analysis indicates that the trough continued its rapid movement during the second 12 hr. The contour gradient tightened at the same time that the southern portion of the trough flattened. Both barotropic models are only slightly slow in their predictions of the trough position over northern Michigan. They are both closer to the observed position than is the baroclinic model. The southern extension of the trough is more accurately predicted by the fine-mesh barotropic model. All three models have a height error of approximately 100 m in the vicinity of Lake Superior. None exhibit the detail evident in the 24-hr analysis (fig. 3A). This suggests that the retention of smaller scale features hinges not only upon greater spatial resolution but also upon greater resolution of relevant physical processes as well.

5. CONCLUSIONS AND FUTURE PLANS

It should be noted that the foregoing comparison of the forecasts by the three models is of limited utility, since there are significant differences in the models not only in their physical applicability and mathematical formulation but also in the representation of the initial state of the atmosphere. Although in this particular case the fine-mesh forecast is quite competitive with the results obtained with the currently used models, the primary significance of the reported results lies in the unique character of the numerical model. The feasibility of solving a primitive equation model over a limited area without an initialization scheme and with the use of only the simplest of boundary conditions was hardly anticipated.

In retrospect, however, the results obtained by Bushby and Timpson (1967) and by Shuman (1962) can be seen to have augured well for this approach. The instability encountered by Bushby and Timpson when they used analogous boundary conditions may have been due to the complexity of the boundary in the staggered grid approach. The large amplitude of the gravity mode in Shuman's result was most likely controlled by our use of the Euler-backward time integration method. A detailed analysis of the difference system and the boundary conditions used in the fine-mesh model is to be undertaken shortly.

The work reported above was auxiliary to the development of a limited area fine-mesh version of the NMC primitive equation baroclinic model which is being undertaken by Lt. Col. Howcroft and Maj. Desmarais of the U.S. Air Weather Service's Operating Location 10. The good result obtained with the barotropic model is considered to be a favorable omen for success with the baroclinic model.

TABLE 1.—*Weights used in smoother*

	I−3	I−2	I−1	I	I+1	I+2	I+3
J+3	1	0	−9	−16	−9	0	1
J+2	0	0	0	0	0	0	0
J+1	−9	0	81	144	81	0	−9
J	−16	0	144	256	144	0	−16
J−1	−9	0	81	144	81	0	−9
J−2	0	0	0	0	0	0	0
J−3	1	0	−9	−16	−9	0	1

APPENDIX

The smoother used to process the forecasts is the 49-point operator whose weights (multiplied by 1024) are shown schematically in table 1.

The response curve for a one-dimensional wave yields unity for wave number 0 and 0 for the two-grid-interval wave. The response curve plotted versus $\cos k\,\Delta x$ (with k the wave number and Δx the grid interval) has zero slope at wave number 0 and at the wave number corresponding to the two-grid-interval wave.

ACKNOWLEDGMENTS

This project has been undertaken as a joint effort of Air Weather Service and National Meteorological Center personnel. The present phase of the research has been reported by the NMC contributors, but in significant measure it is also a contribution by Lt. Col. Howcroft and Maj. Desmarais.

The computer programming was performed by Mrs. Doris Gordon of the NMC Data Automation Division (DAD). The computational routine used to extract analysis data and to interpolate to the fine-mesh grid was written by Mr. James McDonell of DAD.

The authors also wish to express their appreciation to Messrs. Halpern and Wang of IBM for several useful discussions of the problems involved in limited area fine-mesh prediction.

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